Direct Tension and Simple Stiffness Tests—Tools for the Fatigue Design of Asphalt Concrete Layers

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A design strategy with fatigue as the major concern and with a check on rutting was developed using creep and direct tension tests as simple tools. This design is appropriate for the heavy-duty asphalt concrete pavements subject to the environmental and traffic conditions that exist in the state of California. Two types of asphalt cements (AR 4000 and AR 8000) with the California standard 0.5-in. maximum size, medium grade, granite aggregate were used. Hveem stabilometer tests were used to derive the design asphalt contents. Uniaxial unconfined creep tests were conducted to determine the stiffness of the mix. The environments in the state of California were divided into five groups. Full-scale fatigue and direct tension tests were conducted for three temperatures. From these test results equations were developed to predict the fatigue life through the direct tensile stress and simple stiffness. Thus the fatigue testing program, which is time consuming and costly and requires special equipment, was eliminated. Finally several pavement case studies were designed, and the best of these were selected for each of the environmental groups.

With increasing frequency, user agencies in developed and developing countries have been reporting problems with fatigue and rutting distress in the performance of highways at all agency levels—city, county, state, and federal. To minimize these pavement distresses, mixture and pavement design methods should be considered together.

PURPOSE AND SCOPE

The objective of this paper is to present the development of a design strategy, with fatigue as the major concern, using simple tools such as direct tension and uniaxial creep tests. The design system is appropriate for heavy-duty asphalt concrete pavements (AC) subject to traffic and environmental conditions such as those in the state of California. This work concentrates on the development of solutions to mitigate fatigue with a check on rutting. This paper does not cover the design procedure for rutting; however, a check on rutting was done for the sake of completeness of the design procedure. Other forms of distresses (for example, thermal cracking and raveling) are not included in this study. This study is limited to hot-mixed asphalt concrete, excluding, for example, open-graded friction courses and drainage layers.

There are no design charts that cover all the temperature conditions in California available to field engineers for designing highways with fatigue as the major concern; full-scale fatigue testing for at least two or three temperature conditions is necessary. Fatigue testing is time consuming and costly and requires special equipment. The materials studied in this investigation are commonly used in the state of California. Therefore, the development of a design procedure for heavy-duty asphalt concrete pavements that does not require fatigue testing and that incorporates charts that cover the traffic and environmental conditions in the state would be a significant benefit to the field engineer.

MATERIALS AND MIXTURE PROPERTIES

The aggregates and asphalt use, requisite properties, test methods, and criteria to define these properties were given previously (*1*). The properties of the desired mixture, with some of the factors that influence these properties, were also given before (*1*). Past experience at the University of California indicated that AR 4000 and AR 8000 asphalt cements with the properties given in Table 1 and Watsonville granite aggregate with 0.5-in., maximum-size medium gradation (California standard) would pass these standards and requirements for the preparation of asphalt concrete mixes for constructing heavy-duty pavements.

The Hveem stabilometer method was used to determine the design asphalt content (Figure 1). For Class A concrete, California standard (*2*) stipulates a minimum relative stability of 37. Figure 1 indicates that a 5.5 percent asphalt content meets this requirement. To reflect the quality control during the construction, a lean of 0.3 percent asphalt content should be provided (*2*). Therefore an average design asphalt content of 5.2 percent (by weight of aggregate) was selected for both asphalts.

SAMPLE PREPARATION, TESTING EQUIPMENT, AND TESTING TECHNIQUES

Sample Preparation

Two types of mixes were prepared using Watsonville granite aggregate and AR 4000 and AR 8000 asphalt cements for the gradation selected. All the samples were compacted using the Triaxial Institute kneading compactor. For creep tests, cylin-

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TABLE 1 Properties of Asphalts Used in Study

	AR-8000 CR88R-5009	AR-4000 CR88R-5020
Penetration at 77F. dmm	46	72
Viscosity at 140F. poise	3786	2125
Viscosity at 275F. cSt.	425.8	350.8
RTFC Resudue		
Penetration at 77F. dmm	29	37
Viscosity at 140F. poise	8764	4882
Viscosity at 275F. cSt.	620.8	501.4

(Tests are performed by Chevron Research Corporation)

drical specimens 4 in. in diameter and 9 in. in height were initially compacted. Then the material at the ends was trimmed off with a diamond saw to produce the final specimens about 8 in. in height. The top and bottom surfaces were then capped with a thin layer of hydrostone to obtain smooth surfaces for load application. Fatigue beams 4 × 3.75 in. in rectangular sections and 15 in. in length were cast in three layers. Then specimens 1.5 × 1.5 × 15 in. were cut using a diamond saw after freezing the sample for 8 hr at 5°F. From one fatigue sample, two direct tension specimens, each 1.5 × 1.5 × 6 in., were cut by the diamond saw.

Test Procedure

Specific gravity and air void content were determined and cross-sectional measurements were taken for all specimens before testing. The air void contents for the 6 and 5.2 percent asphalt content samples were 4.8 and 6.5 percent with coefficients of variation of 0.1 and 0.1, respectively.

Creep Tests

Creep tests were performed in axial compression in the unconfined condition. The detailed procedure followed in conducting the creep test is beyond the scope of this paper and is given elsewhere (*3*). Tests were performed at temperatures of 77°F, 100°F, 120°F, and 140°F. The pressures applied were 22 lb/in.^{2} on AR 4000 specimens at 140°F; all other specimens were tested at 30 lb/in.^{2}. AR 4000 coarse aggregate samples were not tested at 140°F because the mix is unsuitable for withstanding this high temperature. An IBM personal com-

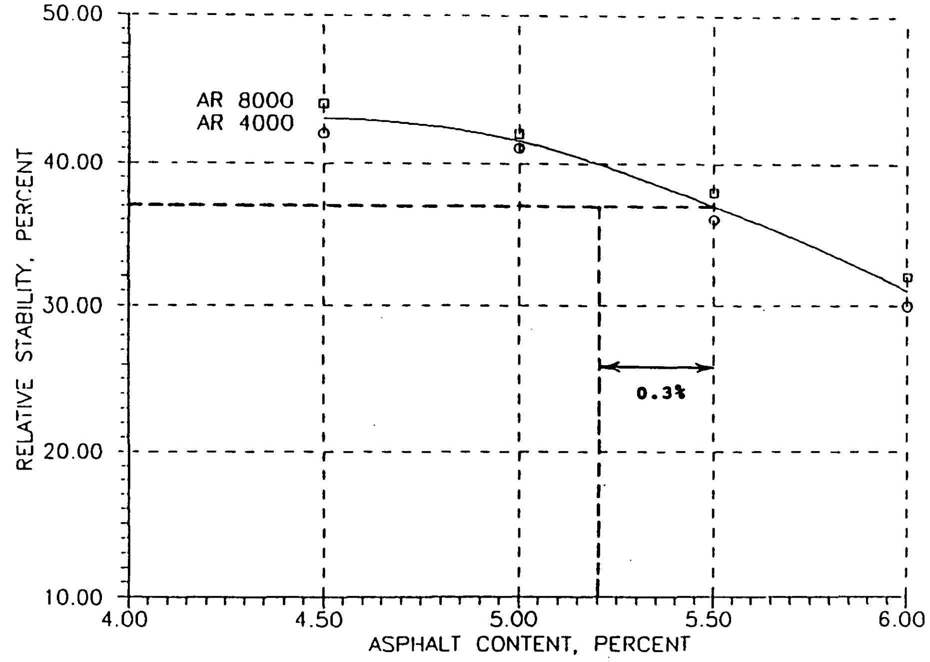

FIGURE 1 Stability versus asphalt content.

puter was used to control the load, record both the load and the deformation, and determine the compliance as a function of time. Creep moduli as a function of time were calculated as the quotient of applied stress divided by total strain at a particular time. A total of 24 creep tests were conducted. Three specimens were tested for each test condition, and the average value was computed. The results of the tests are given in Figure 2. From these results the relationship between the temperature and stiffness at 0.1-sec loading time was derived as shown in Figure 3.

Fatigue Tests

Equipment used by Epps (*4*) was used for conducting fatigue tests. For heavy-duty asphalt pavements controlled fatigue tests are applicable, as suggested by Monismith et al. (*1*). Therefore fatigue tests were conducted under controlled stress conditions. A total of 56 specimens were tested with groups of seven specimens representing one test condition. The test conditions consisted of two stress levels, two types of asphalts, and two temperatures. The two temperatures were 90°F and 110°F. Epps (*4*) tested the same materials at 68°F. The remaining test conditions were the same in both cases [Epps (*4*) and the present study]. Results of Epps were used for 68°F. The loading duration was 0.1 sec with a rest period of 0.5 sec. Although the tests were done at the design asphalt content (5.2 percent) and 0.8 percent more than the design asphalt content (6 percent), the results of 6 percent asphalt content were used for further analysis, for reasons explained in the section entitled Design Implications. Figure 4 (stress-versus-fatigue life relationship) and Figure 5 (strain-versus-fatigue relationship) show the results of 6 percent asphalt content. The stress-versus-fatigue life relationship had better sensitivity with respect to the temperature than that of the strain-versus-fatigue relationship (*4*). This is consistent with the well-established concept of the strain criterion. Therefore the stress-versus-fatigue life relationship was used in the analysis. The influence of temperature on the fatigue bending stress for various repetitions is shown in Figures 6 and 7.

Direct Tension Tests

The testing system similar to the one developed by Epps (*4*) was used in this study. Temperature control was achieved by placing the samples, well packed with two layers of 1-in. thick fiberglass sheets, in the control cabinet. The required temperature was maintained within an accuracy of 1°F. Each test was completed within 5 sec after removing the sample from the temperature control cabinet. While the test was being conducted the insulation remained intact on the sample. Because obtaining complicated test parameters [e.g., the linearity loss of the stiffness of the LCPC (*5*)] is not feasible for the field engineer, the objective of this paper is to use simple tests for the design of highways. A simple parameter in the direct tension test is the tensile stress at break; hence, this parameter was selected in the present study. Epps (*4*) also studied the behavior of asphalt concrete mixes under direct tensile stresses for similar materials with a deformation rate of 0.3 in./min. This rate would produce tensile failure in the specimen in about 0.1 sec, which corresponds to the same timing of loading in fatigue tests. Hence, all the tests were done at a constant strain rate of 0.3 in./min. Tensile stress at break was computed for each specimen for the same variables as those used to define the fatigue test results. The air void content and coefficient of variation were the same for fatigue and direct tension specimens. Two asphalt contents (5.2 and 6 percent) were tested and, as in the case of fatigue, a total of 84 direct tension tests were conducted for each asphalt content (see Figure 8).

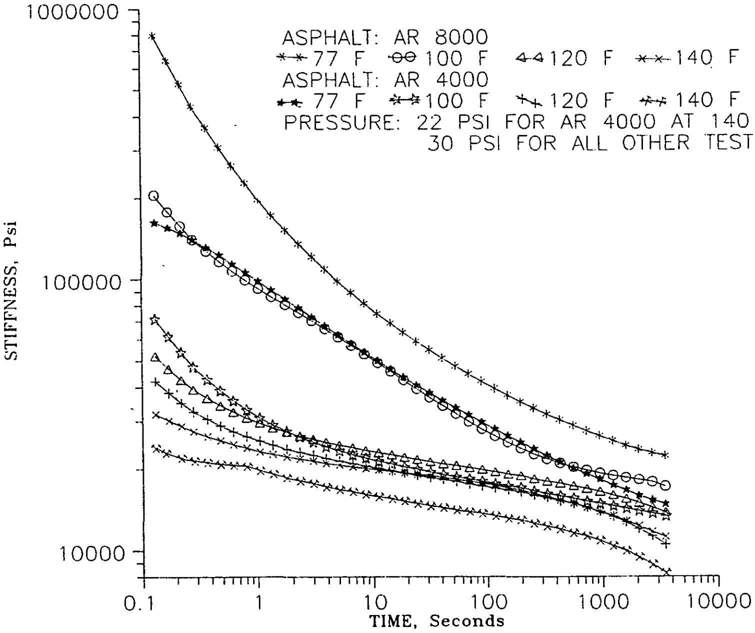

FIGURE 2 Axial creep test results for medium grade aggregates.

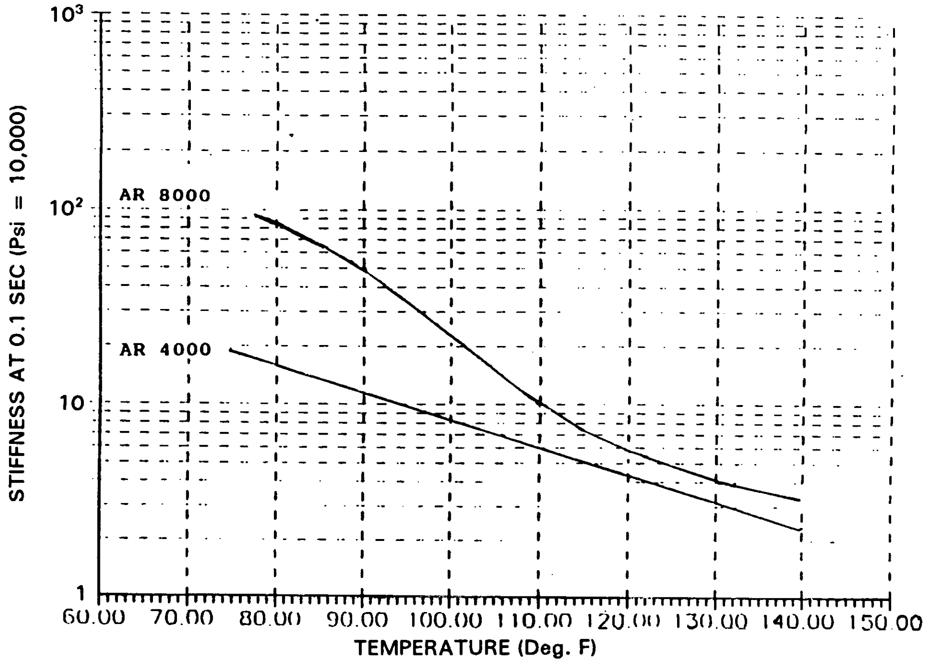

FIGURE 3 Temperature versus stiffness at 0.1 sec; pressure = 30 lb/in.^{2}

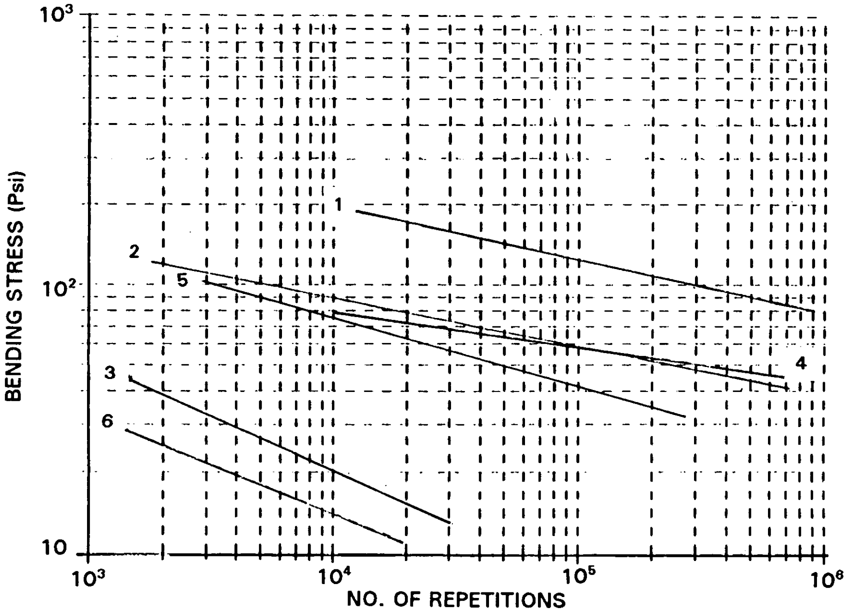

FIGURE 4 Influence of asphalt type and temperature on fatigue life (medium aggregate; 6.0 percent asphalt content; solid lines, AR 8000 [(1), 68°F; (2), 90°F; (3), 110°F]; dashed lines, AR 4000 [(4), 68°F, (5), 90°F; (6), 110°F].

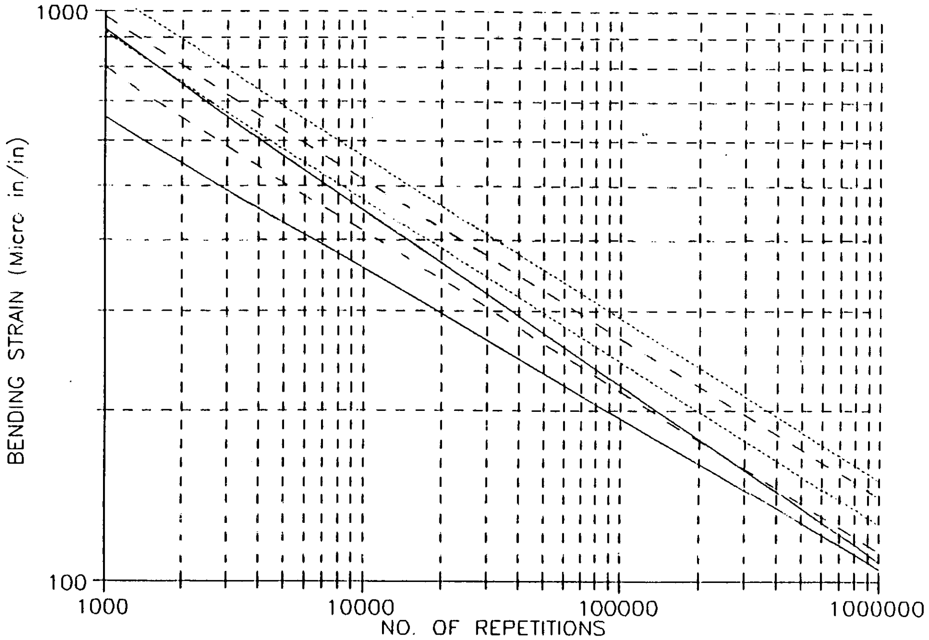

FIGURE 5 Fatigue life versus bending strain: solid lines, 68°F; dashed lines, 90°F; dotted lines, 110°F. In each case, upper line represents AR 4000 and lower line represents AR 8000.

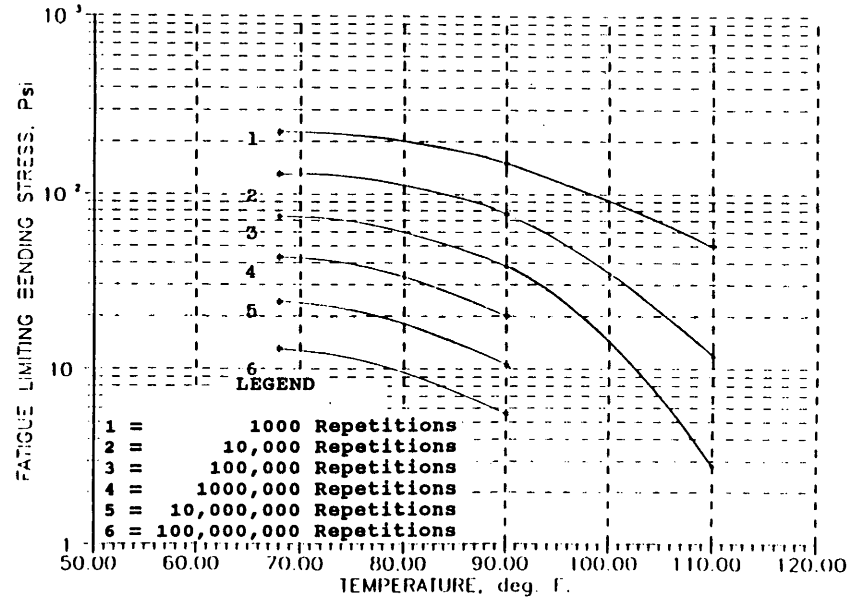

FIGURE 6 Influence of temperature on fatigue limiting bending stress for various repetitions (AR 4000; aggregate, granite, Cal.; asphalt content, 6.0 percent; std. 0.5 in. medium).

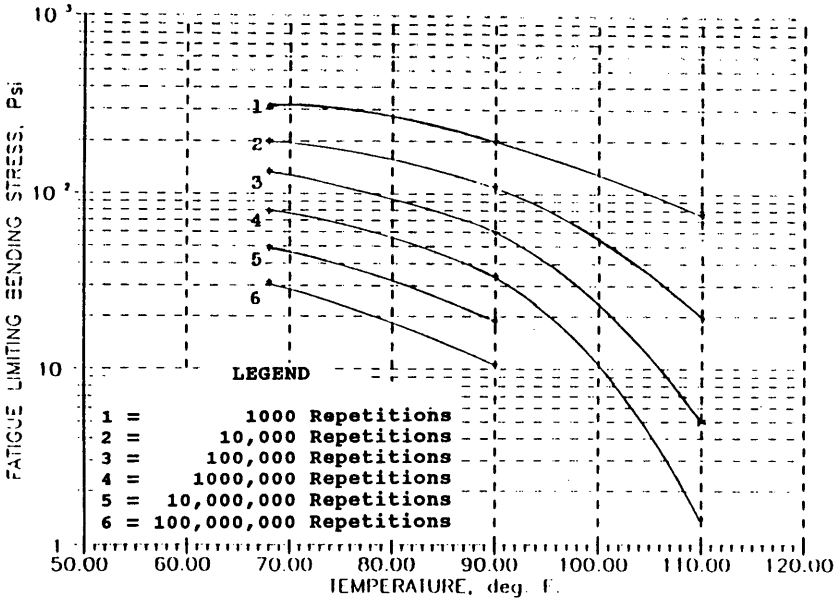

FIGURE 7 Influence of temperature on fatigue limiting bending stress for various repetitions (AR 8000; aggregate, granite, Cal.; asphalt content, 6.0 percent; std 0.5 in. medium).

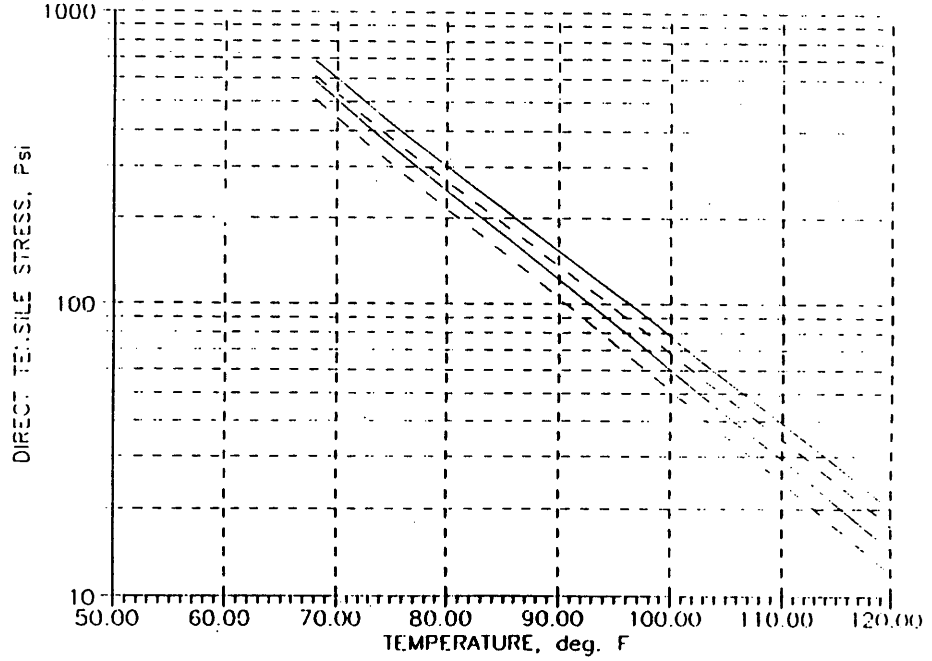

FIGURE 8 Influence of temperature on direct tensile stress (solid lines, 6 percent asphalt content; dotted lines, 5.2 percent asphalt content). In each case, upper line represent AR 8000 and lower line represents AR 4000.

DEVELOPMENT OF DESIGN STRATEGY WITH FATIGUE AS THE MAJOR CONCERN

Influence of Maximum Tensile Stress on Thickness of AC Layer

A multilayer linear elastic analysis was conducted using the ELSYM computer program. About 300 case studies of pavement structural sections were studied, and tensile stresses at the bottom of the AC layer were determined for a set of six variables with the following ranges. These ranges are fairly typical of those usually found in traffic and environmental conditions in the state of California for heavy-duty pavements.

1. Subgrade stiffness, 5,000 to 20,000 lb/in.^{2};
2. Base stiffness, 10,000 to 40,000 lb/in.^{2};
3. AC stiffness, 20,000 to 800,000 lb/in.^{2};
4. Thickness of base, 0 to 24 in.;
5. Thickness of AC layer; 3 to 40 in.; and
6. Tensile stress (bottom of AC), 0 to 450 lb/in.^{2}

The ELSYM computer program consisted of a dual-wheel configuration. Each wheel weighing 4,500 lb had a tire pressure of 100 lb/in.^{2} and a radius of contact of 3.79 in. There was a free space of 3.79 in. between the two wheels. Typical results are shown in Figures 9 and 10.

Relating Direct Tensile and Fatigue Bending Stresses

From the laboratory test results, charts were developed that related the direct tensile stress and the fatigue bending stress for various wheel load repetitions ranging from 1,000 to 100 million, for the temperature range 68°F to 110°F in 5°F increments. Typical graphs are shown in Figures 11 through 13; detailed results were given previously (*3*). The results shown in Figures 6 and 8 were used to develop graphs in Figures 11 through 13. From Figure 8 one can obtain 570 lb/in.^{2} as the direct tensile breaking stress for (a) 6 percent asphalt content, (b) AR 4000 asphalt, and (c) 68°F. From Figure 6 for the same data, one can obtain 225 lb/in.^{2} as the fatigue limiting bending stress for 1,000 repetitions and obtain a point (abscissa, 225 lb/in.^{2} bending stress; ordinate, 570 lb/in.^{2} direct tensile stress) of Curve 1 in Figure 12. Similarly Curve 1 is completed by varying the asphalt content, and Curves 2 and 5 are plotted by changing the load repetitions. A total of 84 fatigue tests consisting of two asphalt contents were conducted in this study. An enormous increase in the repetitive work could produce a slight improvement in the accuracy of the results by increasing the amount of asphalt content. However, this is considered beyond the scope of this paper.

To account for the differences between laboratory and field responses, shift factors are necessary to translate laboratory fatigue characteristics into those considered to be representative of in situ performance. Because of mix age, stiffness of in-service pavements increases for a considerable duration. However, once microcracks start (when the major portion of pavement life is consumed) the stiffness starts decreasing. For thick asphalt pavements (controlled stress fatigue tests) an increase in stiffness increases the fatigue life. Although the influence of age hardening on the fatigue life of individual pavement varies, this phenomenon leads to a conservative design. For tests in which there are rest periods between load applications, usually a factor less than 20 is used (*6*). Finn et al. (*7*) suggested a factor of 13 for predicting up to 10 percent cracking in the wheelpath area for California-type mixtures. This factor was used in the present study because the materials used herein are commonly used in the state of California for

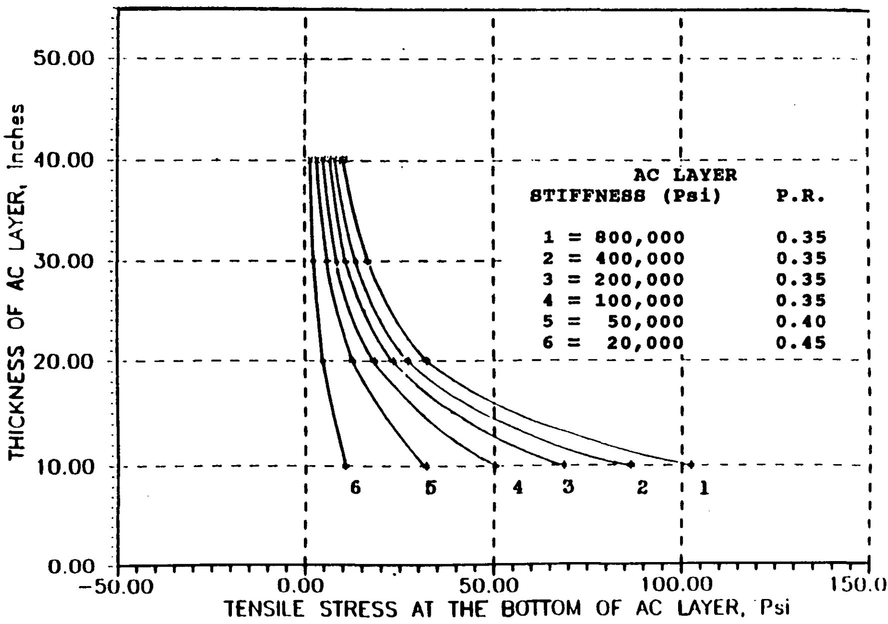

FIGURE 9 Full-depth AC pavement thickness versus tensile stress in AC layer (base thickness, 0 in.; subgrade, E = 10,000 lb/in.^{2}; P.R. = 0.35).

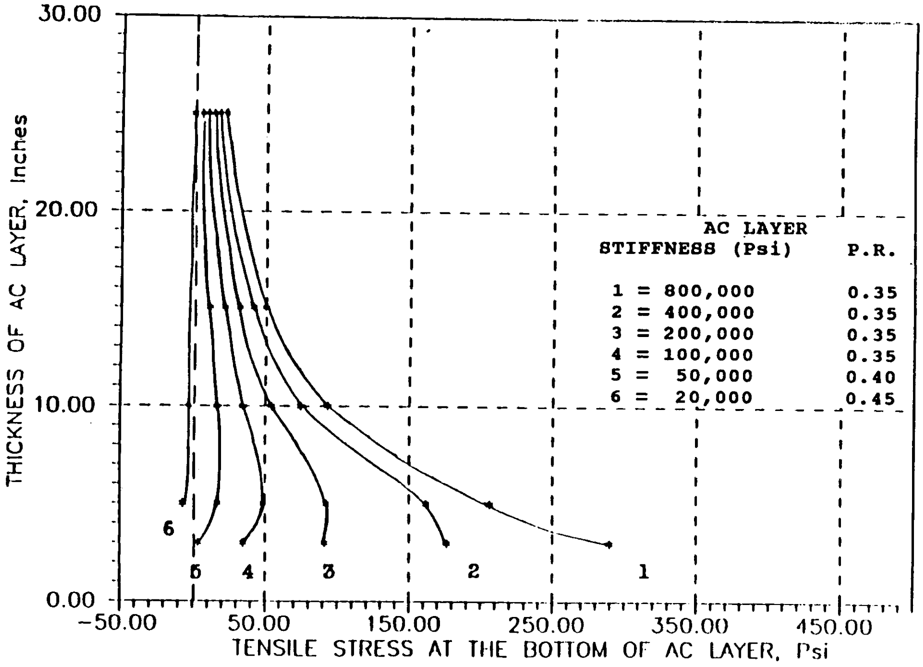

FIGURE 10 Thickness versus tensile stress in AC layer. Base: h = 12 in.; E = 20,000 lb/in.^{2}; P.R. = 0.35. Subgrade: E = 10,000 lb/in.^{2}; P.R. = 0.35.

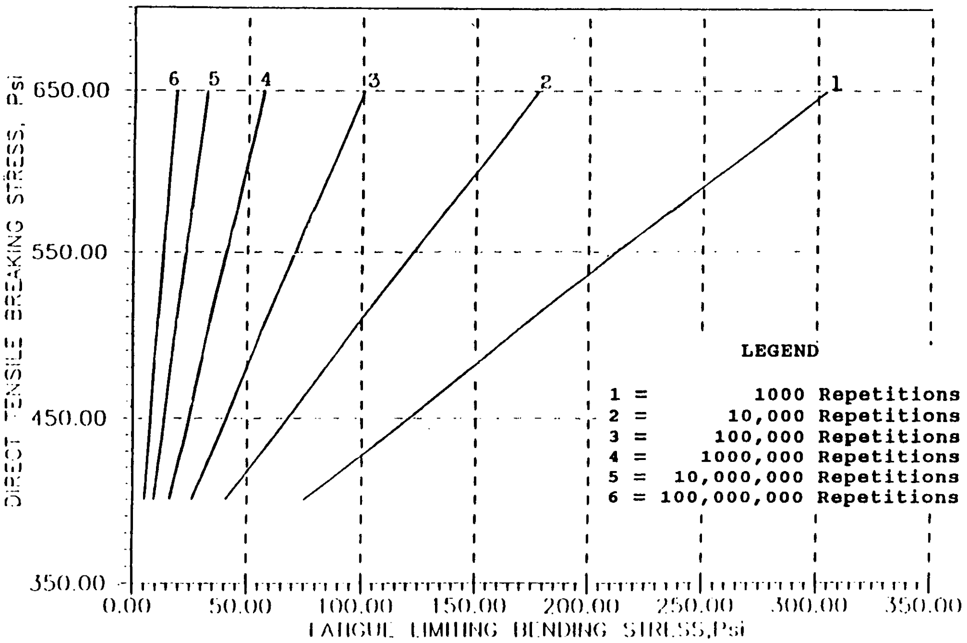

FIGURE 11 Direct tensile stress versus fatigue bending stress for various repetitions (AR 4000; aggregate, granite; 68°F; Cal. std. 0.5 in. medium).

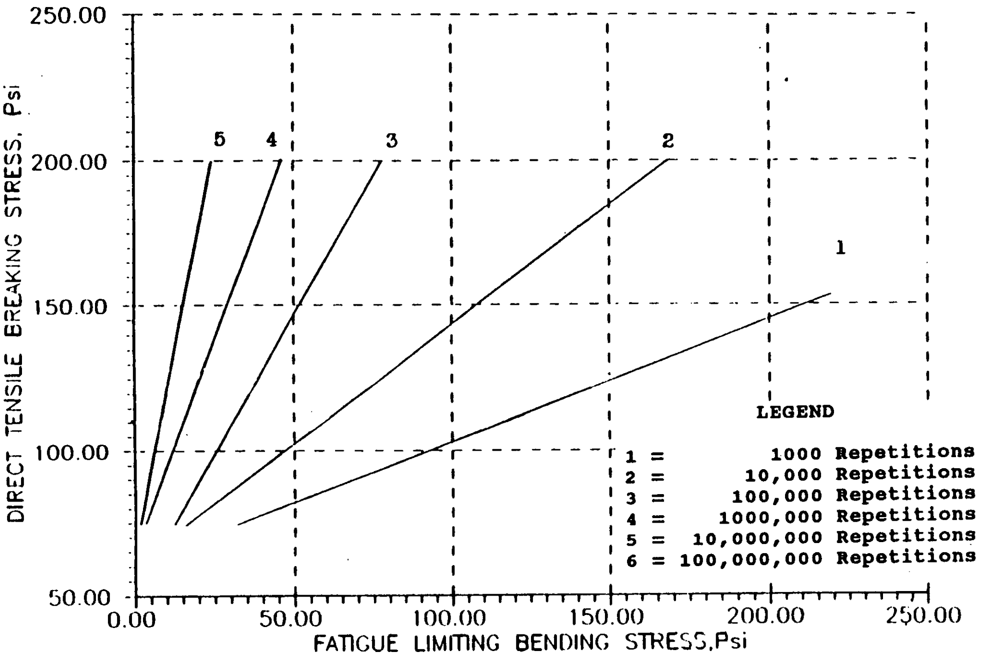

FIGURE 12 Direct tensile stress versus fatigue bending stress for various repetitions (AR 4000; aggregate, granite; 90°F; Cal. std. 0.5 in. medium).

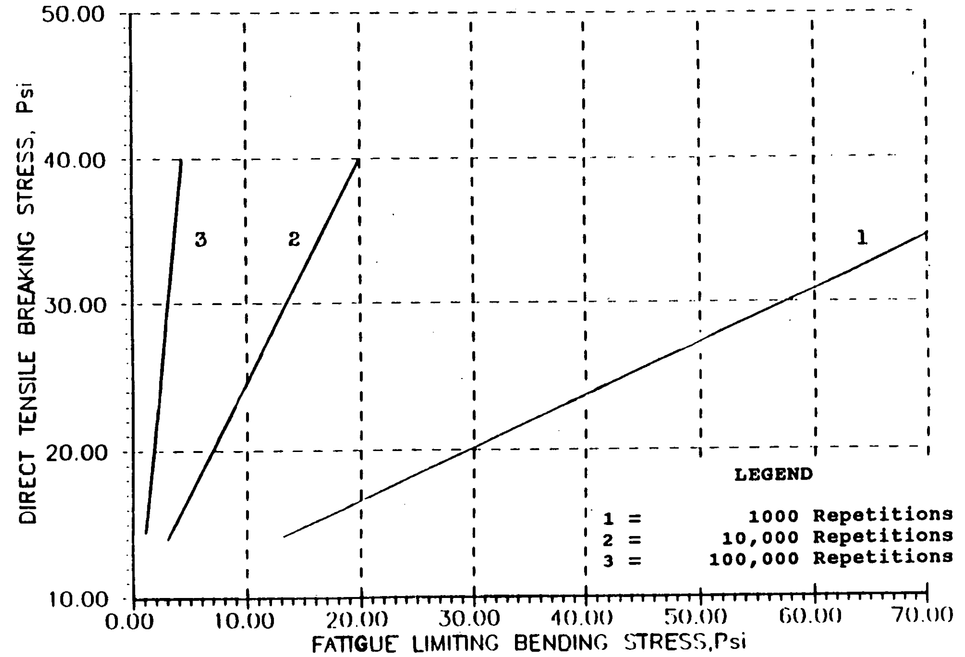

FIGURE 13 Direct tensile stress versus fatigue bending stress for various repetitions (AR 4000; aggregate, granite; 110°F; Cal. std. 0.5 in. medium).

the construction of heavy-duty asphalt pavements. The number of load repetitions in Figures 11 through 13 represent the laboratory fatigue load repetitions. In selecting the design traffic (in terms of cumulative standard axles), the load repetitions of Figures 11 through 13 are multiplied by the factor 13.

Categorization of Environmental Conditions of California

Table 2 gives a summary of the five categories with a typical example city in California. For these zones the mean monthly air temperatures (MMAT) were averaged from data taken during the past 30 years (*8*). The mean monthly pavement temperatures (MMPT) were calculated according to Witczak's equation (*9*).

First Trial Thickness

Once the location and design traffic are selected, trial thickness can be calculated using the charts shown in the design manual of the Asphalt Institute (*10*). An example chart is shown in Figure 14. From this chart AC layer thickness can be obtained if equivalent single-axle load (EAL), subgrade resilient modulus (MR), aggregate base thickness, and MMAT are known.

Tensile Strength of Mix

The relationships between tensile stress at break and temperature are shown in Figure 8. Alternately, field engineers can use the results of direct tension tests of their mixes.

Stiffness of Mix

The stiffness of the mix was obtained from the results of the creep tests as shown in Figure 3, or field engineers can use the results of creep tests of their mixes.

Determination of Fatigue Bending Stress

For the highest MMPT (usually this occurs in July), the fatigue bending stress can be found from Figures 11 through 13 for the appropriate values of direct tensile stress and design traffic.

Second Trial Thickness

For a selected type of pavement structure (e.g., a pavement with a 24-in. thick untreated aggregate base), with the stiffness of the mix and the fatigue bending stress obtained as described above, the AC layer thickness can be obtained from Figures 9 and 10. The fatigue bending stress corresponds to the highest

TABLE 2 Classification of Overall Temperature Conditions

	CITIES BY GROUPS	AVERAGE YEARLY AIR TEMP. °F	AVERAGE YEARLY AIR TEMP. FOR THE GROUP °F	AIR TEMP RANGE JAN. MIN. °F	AIR TEMP RANGE JULY MAX. °F
I	VERY HOT				
	Death Valley	75.3			
	Needles FAA Airport	73.2	73.2	52.1	97.2
	(This is taken as Representative city for group I)				
	Barstow	69.0			
II	HOT				
	Bakersfield	63.3			
	Modesto	61.4			
	Fresno	63.9	63.9	43.0	86.0
	(This is taken as Representative city for Group II)				
III	MODERATELY HOT				
	Sacramento Airport	59.9	59.9	42.4	77.0
IV	COASTAL				
	San Diego (Extreme South)	64.5			
	Eureka (Extreme North)	52.4			
	San Francisco	58.6	58.6	50.0	64.1
	(This is taken as Representative city for Group IV)				
V	COLD				
	Eureka	52.4	52.4	47.9	58.6

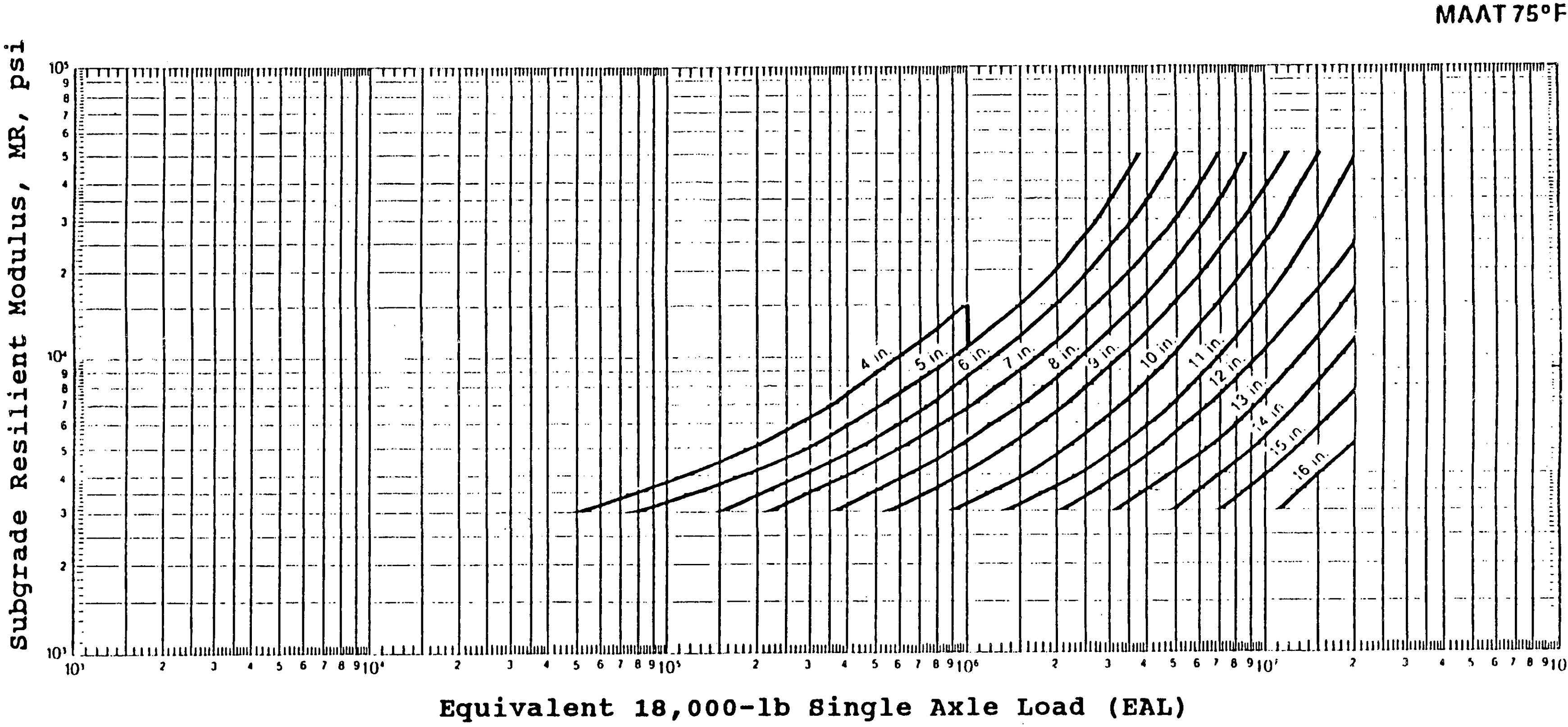

FIGURE 14 Asphalt Institute chart for determining trial thickness (*10*) (untreated aggregate base, 12-in. thickness).

MMPT value. Because an increase in temperature reduces the viscosity of asphalt (hence the stiffness of mix) logarithmically, a major portion of the life of the pavement is consumed in the hottest month. Therefore, the second trial thickness targets the performance of the AC layer during the hottest month. The thickness obtained during that month will be modified to reflect the fractions of damage to the life of the pavement during the other months, as shown in the third trial thickness. This thickness is sufficient to carry traffic during the hottest month in every year during the design period. Experience has shown that the final design thickness usually is within a range of 1 and 1.5 times the second trial thickness.

Third Trial Thickness

The third trial thickness involves an iterative process. The second trial thickness was multiplied by a factor of 1.25. Using Figures 9 and 10 for the values of the second trial thickness and the stiffness of the AC layer obtained earlier, the tensile stress at the bottom of the AC layer was found. From the set of MMPT values and the direct tensile and fatigue bending stresses, the cumulative number of standard axles that possibly can pass were obtained each month (Figures 11 through 13).

By applying the cumulative damage hypothesis (the ratio of the actual number of axles that need to pass divided by the possible number of axles that can pass) the fraction of design life consumed was calculated for each month of the design period.

If the sum of the fractions of life consumed was less than unity, then the third trial thickness became the final design thickness; otherwise further iterations were continued until the cumulative damage fraction became less than unity.

Subgrade Vertical Strain Criterion

The subgrade vertical strain criterion was verified by using the Asphalt Institute's equation, and it was found that all the sections satisfied the criterion.

Case Studies for Fatigue Design

A total of 19 case studies consisting of various pavement structural compositions, asphalt types, traffic intensities, and temperature levels were analyzed. These case studies represent a variety of conditions and are appropriate for the design of heavy-duty asphalt concrete pavements in California. Detailed calculations were conducted for full-depth AC and AC with 4, 8, 12, and 24 in. of base for all the environmental conditions. As an example, the detailed calculations are shown in Tables 3 and 4 for Environmental Condition 3.

TABLE 3 Design of Full-Depth AC Layer for Group 3 Conditions

MONTH	MMPT °	DIRECT TENSILE BREAKING PSI	STIFFNESS AT 0.1 SEC PSI	LIMITING BENDING STRESS PSI	# AXLE REPETITIONS POSSIBLE = LIFE * 10^5	FRACTION OF LIFE CONSUMED
J	52.0	>1000	440,000	>25.0	>>8.3	Negligible
F	57.3	>1000	410,000	25.0	>>8.3	Negligible
M	60.9	940	390,000	24.5	>8.3	<0.01
A	66.4	640	330,000	23.5	>8.3	<0.01
M	73.4	390	260,000	22.5	190	0.04
J	80.3	240	180,000	21.3	60*	0.138
J	85.3	170	170,000	21	25	0.33
A	83.8	185	175,000	21.2	60	0.14
S	81.1	240	195,000	21.5	97	0.09
O	72.2	465	270,000	22.6	480	0.017
N	60.7	950	395,000	24.6	>8.3	<0.01
D	52.8	>1000	450,000	>25.0	>>8.3	Negligible

Fraction of life consumed = 0.785

1st trial thickness = 14 inches

2nd trial thickness = 19 inches

Design thickness = 21 inches

TABLE 4 Design of AC Layer with 12-in. Base for Group 3 Conditions

MONTH	LIMITING BENDING STRESS psi	NO. OF AXLE REPETITIONS POSSIBLE * 10 E5	FRACTION OF LIFE CONSUMED
J	>30.0	>>8.3	Negligible
F	30.0	>>8.3	Negligible
M	28.1	>>8.3	Negligible
A	23.3	550	0.015
M	20.4	180	0.046
J	20.3	65	0.128
J	20.0	27	0.307
A	20.2	65	0.128
S	20.9	98	0.085
O	23.7	440	0.019
N	28.3	>>8.3	Negligible
D	30.0	>>8.3	Negligible

Fraction of life consumed = 0.728

Design thickness = 19

Development of Equivalency Factors

The influence of base thickness, ranging from 0 to 24 in., on the thickness of the AC layer is shown in Figure 15. From these graphs equivalency factors were developed describing the relationships between the thicknesses of the AC and the base layers for all the environmental conditions, as shown in Table 5.

Determination of Optimal Thickness of the AC Layer

For each location and type of material used, there exists a cost relationship between the thickness of the AC layer and that of the base layer. Assuming a cost ratio of 3.5 (i.e., the cost of 1 in. of AC layer is equal to the cost of 3.5 in. of base), the thickness of the AC layer was determined from Table 6 for each environmental condition. For example, from Figure 14 and Table 5 it is seen, in the case of Environmental Condition 1, that 1 in. of base can reduce the design thickness of AC layer by about 1 in. for the first 4 in. of base thickness. Since the cost differs by a factor of 3.5, this is the largest saving and hence the strongest argument for the AC to be replaced by the base. Using a similar justification, up to 9 in. of base can be provided. In developing countries an AC layer is usually several times costlier than that of the base (because of the high cost of asphalt and cheap manual labor); therefore, a cost ratio of 1:10 (AC:base) might be appropriate. Table 6 also shows the design results with an optimal base for this cost ratio. A summary of the design results with fatigue as the major concern is provided in Table 7.

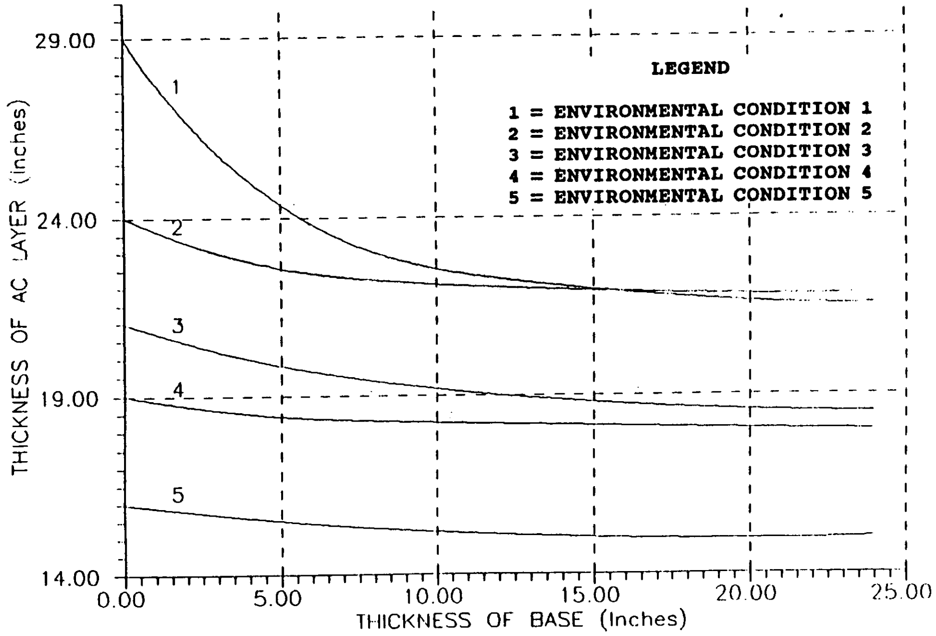

FIGURE 15 Influence of base thickness on thickness of AC layer for the five environmental conditions.

TABLE 5 Development of Equivalency Factors of AC Thickness for 1-in. Base Thickness (1 in. AC = 10 in. UTB)

Environmental	RANGE OF BASE THICKNESS			
Group	0-4	4-8	8-12	12-24
I	1.0	0.5	0.175	0.058
(one in. of AC is reduced by	one	two	six	seventeen inches of base)
II	0.375	0.1	0.025	0.017
(one in. of AC is reduced by	two & half	ten	forty	sixty inches of base)
III	0.25	0.15	0.1	0.04
(one in. of AC is reduced by	four	six & half	ten	twenty-four inches of base)
IV	0.125	0.05	0.03	0.015
(one in. of AC is reduced by	eight	twenty	twenty-three	sixty-six inches of base)
V	0.10	0.07	0.035	0.025
(one in. of AC is reduced by	ten	fourteen	twenty-eight	forty inches of base)

Equations For Predicting Fatigue Life

For each environmental condition, during the four most influential months (June, July, August, and September, which account for about 97 percent of the consumed life) seven data sets of MMATs were obtained for alternate years from 1976 through 1988 (*11*). From these MMATs, using Witczak's equation (*9*), MMPTs were calculated. Direct tensile stress, stiffness value, and fatigue life of the asphalt concrete were also calculated using the procedure explained in previous sections. Multiple regression equations were derived from about 28 data observations, and a summary of the statistical analysis is given in Table 8. Large correlation coefficients ranging from 0.82 through 0.93 were obtained between the independent and dependent variables, as shown in Table 8. The correlation coefficients are statistically significant at the 95 percent confidence interval.

$$\text{Log } N_f = 0.112 * T + 0.036 * S_{\text{mix}} + 0.292 \qquad (1)$$

(Environmental Condition 1)

TABLE 6 Optimum Base and AC Thicknesses for 10-in. Base = 1 in. AC and 3.5-in. Base = 1 in. AC

Environmental Group No.	One inch of AC = 10 inches of Base		3.5 inches of Base	
	Base (in.)	AC (in.)	Base (in.)	AC (in.)
I	14	22	9	22.8 say 23
II	8	23	5	22.4 say 23
III	12	19	4	20.0
IV	3	19	2	18.7 say 19
V	4	16	Full Depth	16.0

All AC thicknesses are rounded off to next inch.

TABLE 7 Summary of Design Results with Fatigue as the Major Concern

Env. Cond.	Design Traffic Std. Axles (Millions)	Stiffness of Subgrade (Psi)	Stiffness of Base (Psi)	Max. MMPT (°F)	Asphalt Type	Design Thicknesses: Full Depth AC (In)	With Opt. Base: Base (1" AC = 3.5" Base) (In)	With Opt. Base: AC (In)
1	13	20,000	40,000	107.6	AR8000	29	9	23
	1	20,000	40,000	107.6	AR8000	15	4	14
2	130	10,000	20,000	92.2	AR8000	24	5	23
	10	10,000	20,000	92.2	AR8000	16	4	15
3	130	10,000	20,000	85.3	AR4000	21	4	20
	10	10,000	20,000	85.3	AR4000	14.5	2	14
4	130	5,000	10,000	70.4	AR4000	19	2	18.6 (rounded to 19)
	10	5,000	10,000	70.4	AR4000	14	2	13.8 (rounded to 14)
5	130	5,000	10,000	65.4	AR4000	16	0	16
	10	5,000	10,000	65.4	AR4000	13	0	13

$$\text{Log } N_f = 0.0068 * T + 0.0274 * S_{\text{mix}} - 0.961 \qquad (2)$$

(Environmental Condition 2)

$$\text{Log } N_f = 0.0021 * T + 0.0968 * S_{\text{mix}} - 0.177 \qquad (3)$$

(Environmental Condition 3)

$$\text{Log } N_f = 0.0023 * T + 0.0447 * S_{\text{mix}} + 0.541 \qquad (4)$$

(Environmental Condition 4)

$$\text{Log } N_f = 0.00023 * T + 0.00116 * S_{\text{mix}} + 1.236 \qquad (5)$$

(Environmental Condition 5)

where

N_f = wheel load repetitions (on the highway) in 0.13 million for Equation 1 and 1.3 million for Equations 2 through 5;
T = tensile breaking stress (lb/in.^{2}); and
S_{mix} = stiffness of the mix.

The stiffness of the mix was obtained in uniaxial creep tests conducted at the design asphalt content. The creep tests were needed for checking the rutting distress. Therefore, the results of the creep tests at the design asphalt content were used. The results of creep tests at 6 percent asphalt content could also be used. This would change the coefficients in the regression equations and require extra work on the part of the field engineer.

TABLE 8 Summary of Statistical Analysis of Fatigue Equations

Environmental Condition	R-Squared	Std. Error of Y-est.	T- Values: Calculated: Ten.Stress	T- Values: Calculated: S_{mix}	T- Values: Critical	Degrees of Freedom
1	0.824	0.243	2.168	2.684	2.064	21
2	0.913	0.238	2.141	2.283	2.064	21
3.	0.898	0.122	2.135	3.722	2.048	25
4.	0.934	0.068	7.068	2.178	2.052	24
5.	0.934	0.014	3.225	5.116	2.048	25

Check for Rutting

Using the results of the creep tests, rut depths were verified for the pavement sections by the procedure originally developed by the Shell researchers (*12*) and modified by Monismith et al. (*1*). The rut depths were found to be within acceptable limits, as shown in Table 9.

WORKED-OUT EXAMPLE

Given

The following conditions are assumed: Environmental Condition 3; maximum MMPT = 85.3°F; MMAT = 74.3°F; MMPTs for each month given in Table 3; asphalt, AR 4000; aggregate, California standard medium gradation, 0.5-in. maximum size; base, untreated aggregate 12 in. thick; traffic, 10 million standard axles; subgrade stiffness: 10,000 lb/in.^{2}; base stiffness, 20,000 lb/in.^{2}

Procedure

1. First trial thickness is 12 in. (from Figure 14).
2. Second trial thickness is computed as follows: direct tensile breaking stress at an MMPT of 85.3°F, 155 lb/in.^{2} for 6 percent asphalt content and AR 4000 asphalt (from Figure 8); S_{mix}, 130,000 lb/in.^{2} (from Figure 3); fatigue bending stress, 42 lb/in.^{2} (from Figure 12, for 155 lb/in.^{2} direct tensile stress and from Curve 5). Therefore, second trial thickness = 19 in. (from Figure 10), for the S_{mix} of 130,000 lb/in.^{2} and the fatigue bending stress of 42 lb/in.^{2}
3. Design thickness is 21 in. (from Table 3).

STRATEGY DEVELOPED IN THIS STUDY COMPARED WITH THAT OF OTHER METHODS

LCPC Method

In the LCPC (France) procedure the tensile strain corresponding to 1 million applications is estimated from a regression equation (*5*). The data indicated excellent correlation between the estimated strain and that measured in controlled strain fatigue tests at 10°C (50°F) conducted at a frequency of 25 Hz (*5*). With the data obtained from the test program, an elastic quality indicator was calculated. This elastic quality indicator is the thickness of asphalt concrete required to sustain 1 million repetitions (using the estimated strain at 1 million repetitions from the tensile test sequence) of a 130-kN axle load when the modulus of the subgrade is 100 MPa and the stiffness of the mix is determined from the test data at 10°C and at a time of loading 0.02 sec.

TABLE 9 Summary of Rut Depth Predictions

Sl. No.	Environmental Condition	Asphalt Type	Rut Depth Inches	mm
1	1	AR8000	0.053	1.3
2	1	AR4000	0.067	1.7
3	2	AR8000	0.042	1.0
4	2	AR4000	0.055	1.4
5	3	AR8000	0.040	1.0
6	3	AR4000	0.051	1.3
7	4	AR8000	0.030	0.7
8	4	AR4000	0.036	0.9

Modifications Incorporated into this Study

Effect of Temperature

In this study the effect of temperature, ranging from 68°F to 110°F (which covers the state of California), on the design of asphalt concrete layers can be determined with fatigue as the major concern.

Mode of Loading

Monismith et al. (*1*) have shown that controlled stress type of loading is more appropriate for thick asphalt pavements, whereas a controlled strain mode of loading is more suitable for thin asphalt pavements. In the LCPC method, controlled strain tests were followed, whereas in the present study controlled stress tests were conducted because in this investigation only thick asphalt pavements were considered.

Asphalt Institute Method

Effect of Temperature and Asphalt Type

There is a provision, to some extent, in the Asphalt Institute's method of thickness design for estimating the effect of temperature on the design thickness (*10*). The charts of the MS-1 manual show the influence of mean annual air temperature (MAAT) for a limited range of 45°F to 75°F on the thickness of AC layer for a given subgrade modulus. In this (the Asphalt Institute's) method, MAAT has to be averaged for the entire 1-year period.

The present study can account for the influence of air temperature for each month. In most of the cases, about 75% of the design life of the highway is consumed in the two hottest months. The Asphalt Institute's method does not account for the asphalt type, whereas the present study can determine the influence of two types of asphalts that are used in the state of California (AR 4000 and AR 8000) on the design thickness of the AC layer. Table 10 compares the AC layer thicknesses obtained in the present investigation with those designed by the Asphalt Institute's method. Results from this study at the moderately high air temperature of 75°F using AR 8000 asphalt and at the low air temperature of 60°F using AR 4000 asphalt agree closely with those obtained by the Asphalt Institute's method.

TABLE 10 Comparison of AC Layer Thicknesses Obtained by Study and Asphalt Institute Method (Traffic = 10 million, Subgrade E = 10,000 lb/in.^{2}

ASPHALT INSTITUTE METHOD			PRESENT STUDY					
MMAT	AC THICKNESS		Max. MMPT	Asphalt Type	Tensile Stress	Bending Stress	AC THICKNESS	
	Full Depth AC	12 In. Base					Full Depth AC	12 In. Base
(°F)	(In)	(In)	(°F)		(Psi)	(Psi)	(In)	(In)
75	15	13	83	AR8000	255	45	16.5	16
60	14	12	68	AR8000	700	92	8.5	8
				AR4000	580	52	13.5	13

Influence of Base Thickness on Design Thickness of Asphalt Concrete

The Asphalt Institute's method cannot identify the effect of base thickness on the design thickness of the asphalt layer. The design strategy of the present study determines the optimal base thickness and corresponding AC thickness so that the total project cost is minimized. The maximum base thickness that could used by the Asphalt Institute's method is only 18 in. whereas, in this study, up to 24 in. of base can be analyzed.

DESIGN IMPLICATIONS

The maximum resistance to permanent deformation without the loss of the required stability can be obtained by designing the AC layer with an asphalt content that is obtained by the Hveem procedure. Epps (*4*) showed that optimal fatigue performance for the dense-graded mixes occurs at an asphalt content (by weight of aggregate) about 0.8 percent higher than that of the stability requirement. For all the cases analyzed in this study the minimum thickness of AC layer was 16 in. For this thickness the vertical stress (100-lb/in.^{2} tire pressure and 4,500-lb dual wheel load) at the bottom of the AC layer would be on the order of 3 to 5 lb/in.^{2}, and the pavement temperature would be on the order of 92°F (Environmental Condition 4 has the maximum temperature among all the conditions). For such a low vertical stress and temperature, a slight increase in asphalt content would be justified to obtain the benefit of increased fatigue performance without losing the resistance to permanent deformation. Therefore, only at the bottom 2 in. of the AC layer might the design asphalt content be increased to 5.7 percent (the target content of 6.0 percent was reduced by 0.3 percent because of construction quality control considerations).

SUMMARY

1. Hveem stabilometer tests were used to derive the design asphalt contents.
2. Optimal resistance to fatigue with a check on rutting was obtained by recommending a design asphalt content of 5.2 percent (obtained by the Hveem method) in the AC layer, except in the bottom 2 in. where 5.7 percent asphalt content is recommended.
3. Tables were prepared for the design of heavy-duty pavements with fatigue as the dominant concern for the environment and traffic conditions that exist in the state of California. These tables enable the field engineer to design highways without conducting the fatigue tests, which are costly and time consuming and require special equipment, and with materials commonly used in the state of California (Watsonville granite aggregate and AR 4000 and AR 8000 asphalt cements). The two parameters needed by the field engineer are tensile strength and stiffness of the mix.
4. Equations were derived to predict the fatigue life of the AC layer for each environmental condition by using the direct tensile stress and stiffness of the mix. These equations had large coefficients of correlation between the independent and dependent variables. The correlation coefficients are statistically significant at the 95 percent confidence interval.

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Publication of this paper sponsored by Committee on Flexible Pavement Design.